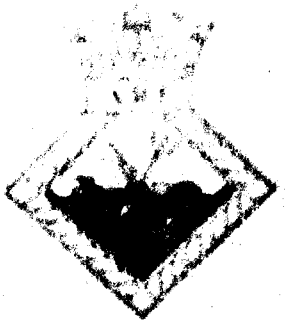
MARCH 1991



EXPERIMENTS ON LOW ASPECT RATIO HYDROPLANES TO MEASURE LIFT UNDER STATIC AND DYNAMIC CONDITIONS

B Ward
A R J M Lloyd

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EXPERIMENTS ON LOW ASPECT RATIO HYDROPLANES TO MEASURE LIFT UNDER STATIC AND DYNAMIC CONDITIONS

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Summary

This Technical Memorandum describes experiments in the Circulating Water Channel to measure lift forces on low aspect ratio hydroplanes under static and dynamic conditions. Empirical equations to represent the results are given.

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Contents

Notation

A	Surface Area of Hydroplane	m^2
a_o	Coefficient of Empirical Equation 3 - Lift Curve Slope for t/c = 0.2	rad^{-1}
a'_o	Modified Coefficient of Empirical Formula 3 for given t/c	
a_1	Coefficient of Empirical Equation 3	
a_2	Coefficient of Empirical Equation 3	
a_e	Aspect Ratio of Hydroplane 2s/c	
c	Chord length	m
C_L	Lift Coefficient	
C_{L_0}	Lift Coefficient Amplitude	
D	Drag Force: Positive to Tail	N
L	Lift Force: Positive Nose to Port	N
N	Force Normal to Hydroplane Positive to Port	N
Re	Reynolds Number	
U	Flow Velocity	m/s
s	Span	m
T	Force Tangential to Hydroplane Positive Forward	N
t	Thickness at quarter chord of hydroplane	m
α	Angle of Incidence Positive Nose to Port	degrees
α_{ST}	Stall Angle of Incidence for t/c = 0.2	radians
α'_{ST}	Stall Angle of Incidence for given t/c	radians
$\dot{\alpha}$	Angular velocity	radians/sec
$\ddot{\alpha}$	Angular Acceleration	radians/sec
ϵ	Phase Angle	radians
ρ	Density of Fresh Water	1000 tonnes/m^3

ω	Frequency	radians/sec
Ω	Sweep Angle	radians

EXPERIMENTS ON LOW ASPECT RATIO HYDROPLANES TO MEASURE LIFT UNDER STATIC AND DYNAMIC CONDITIONS

By B Ward and A R J M Lloyd

1. INTRODUCTION

In support of SUBSIM (Reference 1) the computer program which simulates submarine manoeuvres, there was a need for data on dynamic effects on lift forces for low aspect ratio hydroplanes. A thorough literature search was carried out; previous papers usually described two dimensional experiments at much higher frequencies than those of relevant interest. It was therefore decided to perform some dedicated experiments to obtain the required data.

2. EXPERIMENT

Three NACA 0020 hydroplanes were used of aspect ratios 1, 1.5 and 2 (Figure 1). Each hydroplane had a chord length of 0.26 m and span of 0.13 m, 0.195 m and 0.26 m respectively. A strain gauged stock at the quarter chord position of the hydroplane was attached to a servo to oscillate the hydroplane (Figure 2). The same stock was used for all three hydroplanes. Strain gauge bridges on the stock were calibrated to give normal and tangential forces.

The experiment was conducted in the Circulating Water Channel (Figures 3 and 4). The servo was attached below the CWC floor and the position of the floor was altered to accommodate each hydroplane. A 1 mm space was left between the floor and the hydroplane root. Horizontal flow velocity was maintained at 2.5 m/s.

3. DATA ACQUISITION AND DATA ANALYSIS

The DATS computer package was used for both data acquisition and data analysis. DATS consists of a number of modules which enable mathematical functions to be applied to files of time history data (see DATS User Manual, Reference 2).

Velocity of the flow was measured upstream of the hydroplane using laser doppler velocimetry techniques.

Velocities from the laser, achieved angle from the servo, and normal and tangential forces from the stock were acquired simultaneously. The lift was derived from (see Figure 5)

$$L = N \cos \alpha + T \sin \alpha \qquad (1)$$

The upper tangential force gauge was damaged when the experiment was being rigged and no measurements of total tangential force were possible. The readings from the lower gauge were doubled to allow equation (1) to be used to calculate the lift force. This procedure was not strictly correct but will not have introduced any large errors because the contribution of the tangential force to the lift is very small.

Lift coefficients were calculated using the instantaneous velocity.

$$C_L = \frac{L}{\frac{1}{2}\rho U^2 A} \qquad (2)$$

4. STATIC RUNS

Mean values of α and C_L were taken for static runs over the acquisition time; typically 50 seconds (Figure 6).

Figures 7 to 9 show plots of non dimensional lift C_L against angle of attack for aspect ratios 1, 1.5 and 2 respectively.

Figure 10 shows a plot of stall angle against aspect ratio.

5. OSCILLATING RUNS

Oscillating runs (Figure 11) were carried out at frequencies from 0.055 Hz to 0.386 Hz corresponding to $\frac{\omega c}{U}$ values from 0.036 to 0.252. Frequencies were chosen to correspond to full scale angular rates in the region of 5 degs/sec. The frequency was limited to ensure that rate limiting did not occur in the servo. The average C_L amplitudes were calculated. Plots are shown in Figures 12 to 14. Little variation with frequency was apparent.

Figures 15 to 17 show plots of phase angles against $\frac{\omega c}{U}$ for three different aspect ratios. The phase angles are positive indicating that lift leads incidence. Note the linear trend in the data.

Figure 18(i) to 18(iii) shows continuous plots of C_L against incidence for three oscillating runs with aspect ratio 2 at different frequencies. Incidence amplitude is 35.5 degrees in all cases (above the static stall angle). Note at the lower frequency stall is evident. At the higher frequencies the lift coefficient is higher at zero angle corresponding to greater phase lead. Stalling does not seem to occur at the high frequencies.

6. RAMPING MOTIONS

Figure 19 shows the results of three ramping motion experiments to an incidence of 41 degrees at 6 degs/sec ($\frac{\dot{\alpha} c}{U} = 0.011$) for an aspect ratio of 1.5. In each case the lift coefficient follows the angle of incidence to well above the maximum static value. In other words the hydroplane does not immediately stall. After some time flow separation occurs, the hydroplane stalls and the lift collapses to the value given in Figure 8. High lift is maintained for an apparently arbitrary time.

7. EMPIRICAL EQUATIONS

7.1. Representation of C_L by Second-Order Linear Equations

It is assumed that under dynamic conditions the equation for lift coefficient is

$$C_L = a_o \alpha + a_1 \dot{\alpha} \frac{c}{U} + a_2 \ddot{\alpha} \frac{c^2}{U^2} \tag{3}$$

where $a_0\alpha$ is the static lift curve slope, $a_1\dot{\alpha}$ is the effect of angular rate and $a_2\ddot{\alpha}$ is the acceleration effect.

The following equations can then be derived

$$\alpha_0 \left(- a_2 \frac{c}{U^2} \omega^2 \cos \epsilon - a_1 \frac{c}{U} \omega \sin \epsilon + a_0 \cos \epsilon\right) = C_{L_0} \tag{4}$$

where α_0 is the α amplitude

and C_{L_0} is the C_L amplitude

and

$$\epsilon = \tan^{-1} \left[\frac{- \frac{c}{U} a_1 \omega}{a_0 - a_2 \omega^2 \frac{c^2}{U^2}} \right] \tag{5}$$

Using the experiment results and the least squares plane method the coefficients in equation (4) were derived for each of the three aspect ratios;

a_e	a_2	a_1	a_0
1	0.37	1.12	1.72
1.5	0.44	1.3	1.95
2	0.47	1.4	2.12

The experiment gave lower values than the empirical equation (6) derived by Whicker and Fehlner (Reference 3) at aspect ratio 1.5 and 2:

$$a_0 = \frac{1.8\ \pi\ a_e}{1.8 + \sqrt{4 + a_e^2}} \text{ per radian} \qquad (6)$$

That particular experiment used a NACA 0015 section as opposed to the NACA 0020 used in this study. NACA 0020 sections give reduced values of C_L compared with NACA 0015 (Reference 4). However at aspect ratio 1 the Whicker and Fehlner equation gives lower values than this experiment justifying the conclusion made in Reference 5 - 'that the lift curve slope at very low aspect ratios is seriously under estimated by equation (6)'. Although that conclusion was based on only two results, the results from this experiment give added weight to the statement. Using these assumptions and taking the lift curve slope to be zero at zero aspect ratio formed the basis under which a more general equation was derived for coefficient a_0 ie the lift curve slope:

$$a_0 = 163 \tanh (0.5\ a_e + 2.4) - 160 \qquad \text{per radian } a_e \leq 2$$

$$= \frac{1.66\ a_e}{1.8 + \cos \Omega \sqrt{4 + a_e^2/\cos^4 \Omega}} \qquad \text{per radian } a_e > 2 \qquad (7)$$

A plot can be seen in Figure 20.

As can be seen from Figures 7 to 9 the equation fits the linear part of the experiment data for static conditions very well.

Equations were derived to fit the coefficients a_1 and a_2 in equation (3). Only three points are available and it was assumed that there are no dynamic effects if aspect ratio is zero. It was assumed that the function approaches limits determined by the trend of the data available. A plot of the equations for coefficients a_1 and a_2 can be seen in Figures 21 and 22 respectively.

$$a_1 = 99.3 \tanh (0.61\ a_e + 2.42) - 97.7 \qquad (8)$$

$$a_2 = 1.21 \tanh (0.78\ a_e + 0.68) - 0.71 \qquad (9)$$

The satisfactory fit of the equations can be seen in Figures 12 to 17.

Equation (5) for phase, compared with experimental results in Figures 15 to 17, is best for $a_e = 2$ and adequate for the lower aspect ratios.

7.2. Equation for Stall Angle

An empirical equation was derived from the experiment data on stall angle

$$\alpha_{ST} = 0.113\ a_e^2 - 0.615\ a_e + 1.32 \text{ radians} \quad (10)$$

This gives higher values for all three aspect ratios than that calculated by the formula used in SUBSIM (Reference 1)

$$\alpha_{ST} = 0.075\ a_e^2 - 0.445\ a_e + 1.05 \text{ radians} \quad (11)$$

which is derived from the data in Reference 3. These equations are compared with the experiment data in Figure 10.

The above equation is valid for $1 < a_e < 2$.

8. EFFECTS DUE TO THICKNESS CHORD RATIO

8.1. Correction for Lift Curve Slope

From results quoted in Reference 4, (Figure 23) it can be seen that a change in thickness ratio has an effect on lift curve slope. From these data the following formula has been derived to correct for thickness/chord ratio.

$$a_0' = (0.96 + 1.7\ t/c - 7.1\ t^2/c^2)\ a_0 \quad (12)$$

The formula is valid for data in the range t/c = 0.09 to 0.35.

8.2. Correction for Stalling Angle

Reference 3 gives stall angle data for square tip fins. Using those results and the results from this experiment a general equation for stall angle was derived correcting for thickness ratio.

$$\alpha_{ST}' = (0.36 + 3.2\ t/c)\ \alpha_{ST} \quad (13)$$

9. EFFECTS DUE TO FAIRED TIPS

An unpublished report by the Stevens Institute of Technology discusses the fact that square tip hydroplanes give greater lift forces than faired tip hydroplanes. This was also noted in Reference 3 by Whicker and Fehlner. The conclusion reached in the Stevens report was that the hydroplane tip outboard of the trailing edge span can be assumed to carry no lift. This should be taken into account in SUBSIM by specifying the hydroplane outreach to exclude any faired tip.

10. RANDOM SIGNAL EXPERIMENTS

Following the experiments described in this report a further experiment (Reference 6) was conducted. The 1.5 aspect ratio hydroplane was oscillated using a random signal. Figure 24 shows a plot comparing the lift coefficient derived from equation (3) and a time history of C_L from the random signal experiment. The comparison is very good, confirming the validity of equation (3).

11. CONCLUSIONS

The experiment to examine dynamic effects on oscillating hydroplanes showed the effects to be small but worth noting. The most interesting aspect of the experiment was the delayed stall noted during the ramping motion experiments.

The rapid change in flow velocity at the surface of the hydroplane as it is ramped over causes a rapid change in pressure gradient. There is a delay in the build up of the adverse pressure gradient which allows the hydroplane to support greater lift than during the steady state. This was noted by Ericsson in Reference 7. According to Moore (Reference 8) this delay allows the hydroplane to respond to the change of angle of attack without stall which contributes to the lift overshoot.

Above the stall angle oscillating motions show increased values for C_L compared with static results due to dynamic effects.

No significant variation in C_L was noted over the range of frequencies examined. Phase angles are small; a phase lead of approximately 10 degrees occurs at the highest frequency of 0.386Hz ($\frac{\omega c}{U} = 0.252$). This may be significant for autopilot design.

Effects due to thickness ratio and faired tips should be considered when incorporating any empirical formula derived from this experiment into SUBSIM.

Empirical formulae fit experimental results very well. These formulae should be incorporated into the SUBSIM mathematical model and assessed by further validation of submarine predictions against full scale trial results.

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FIG.1 THREE NACA 0020 HYDROPLANES

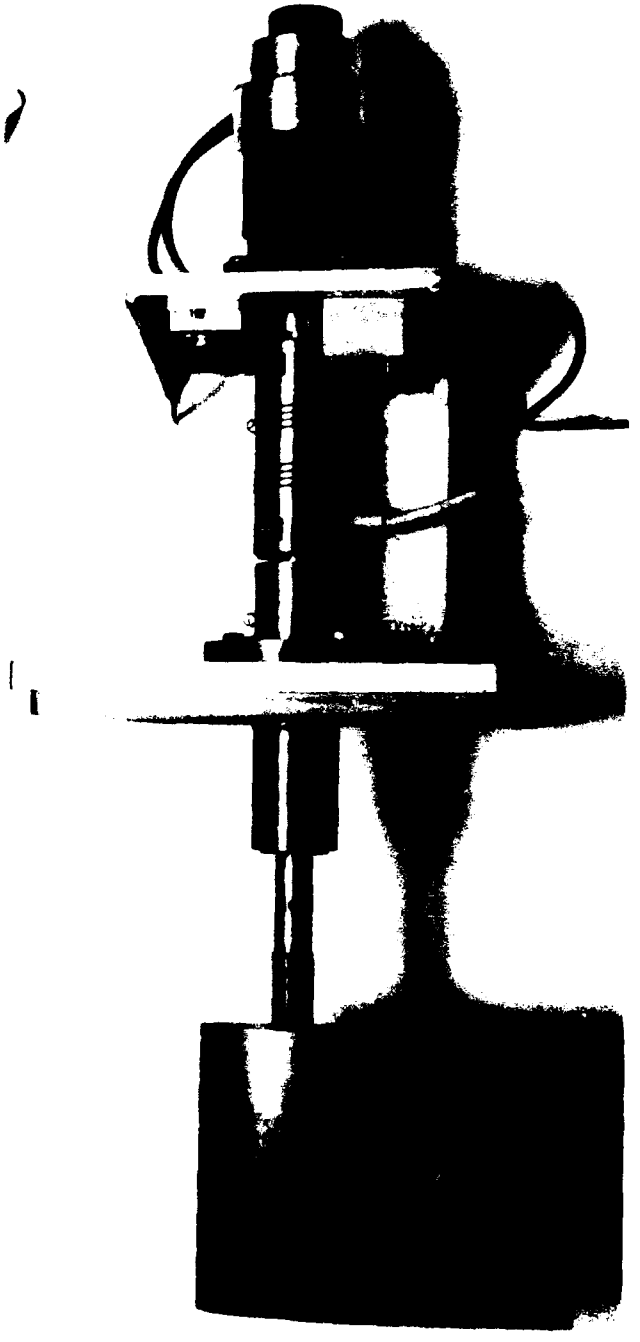

FIG.2 HYDROPLANE ON SERVO

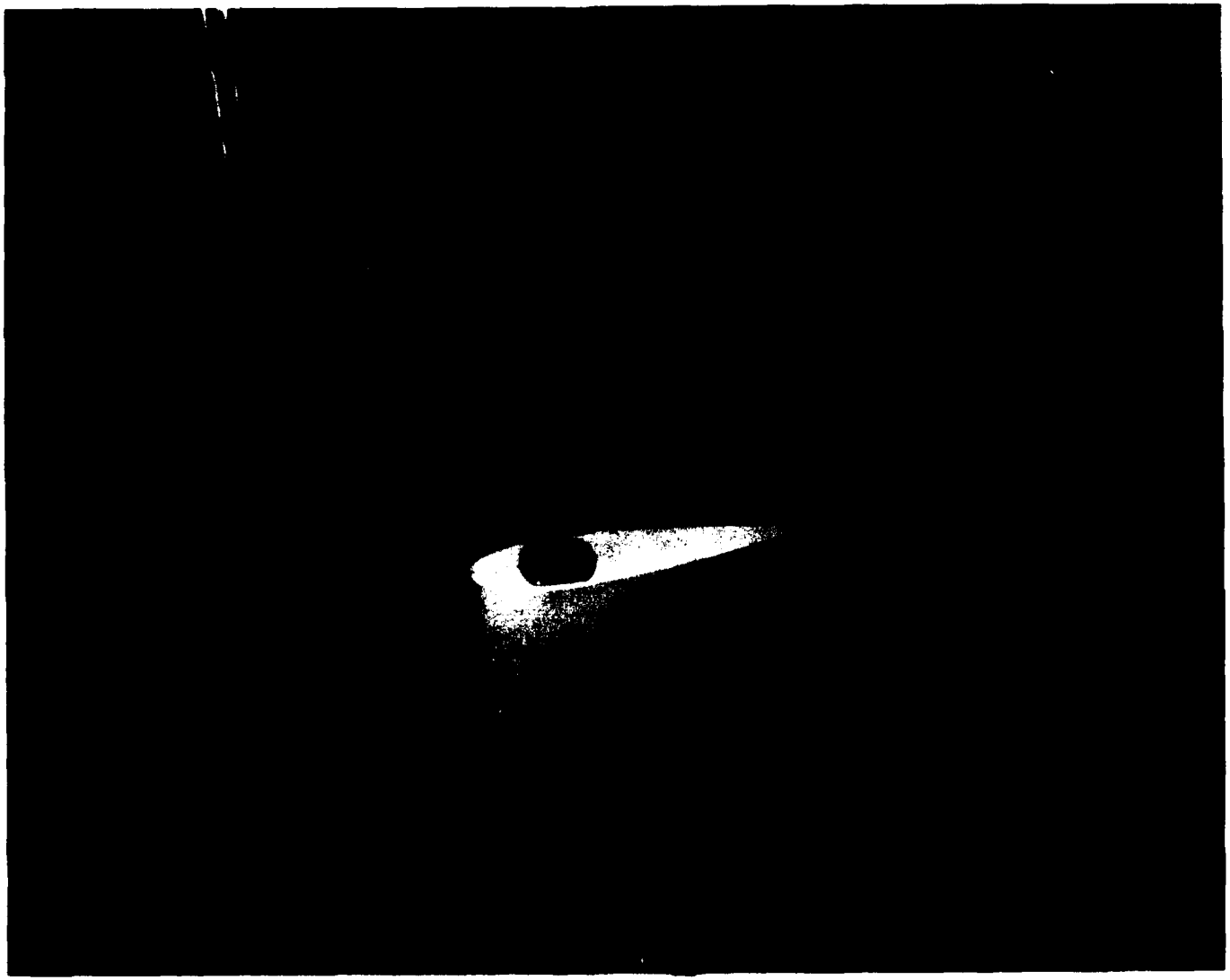

FIG.3 EXPERIMENT IN CIRCULATING WATER CHANNEL

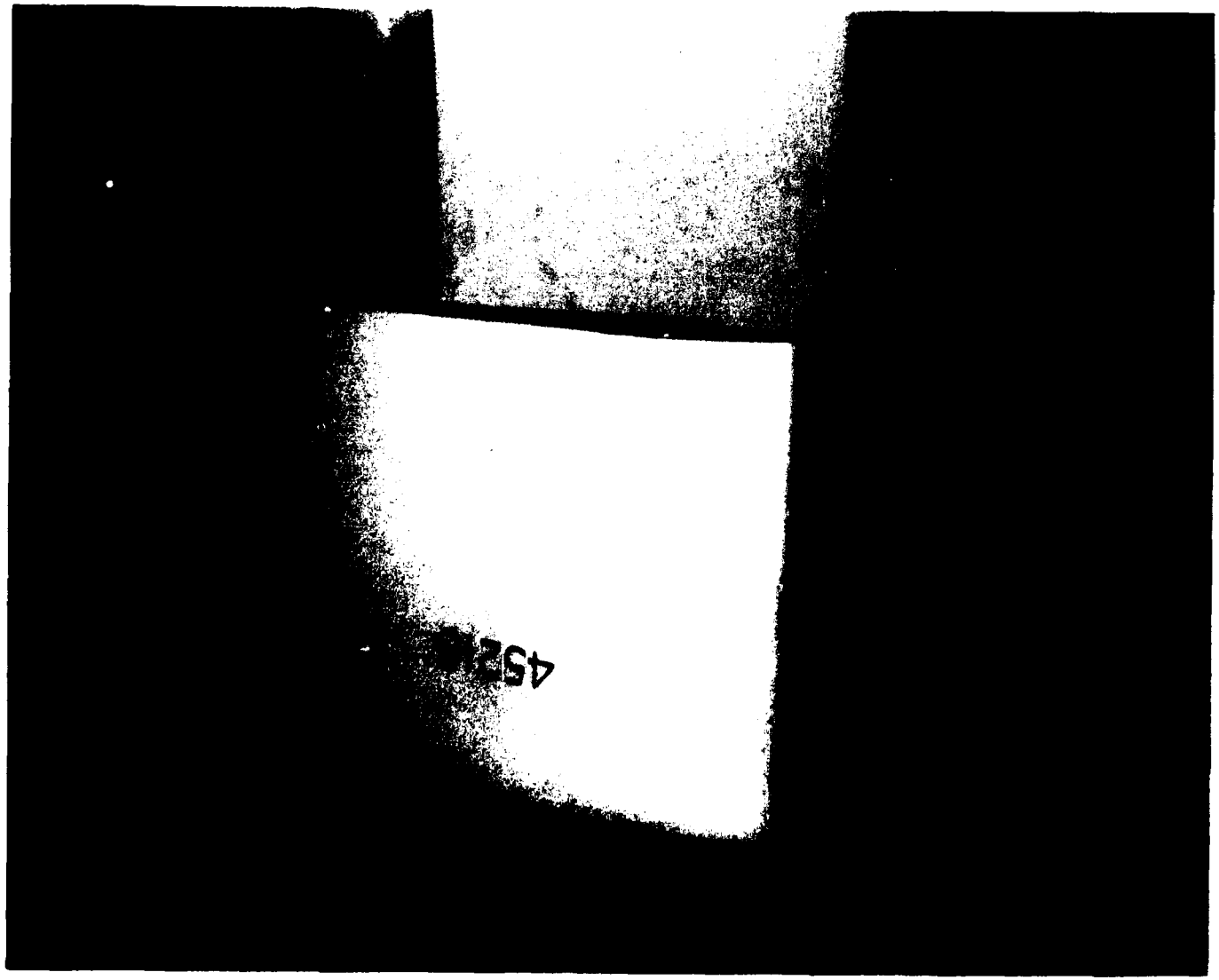

FIG.4 EXPERIMENT IN CIRCULATING WATER CHANNEL

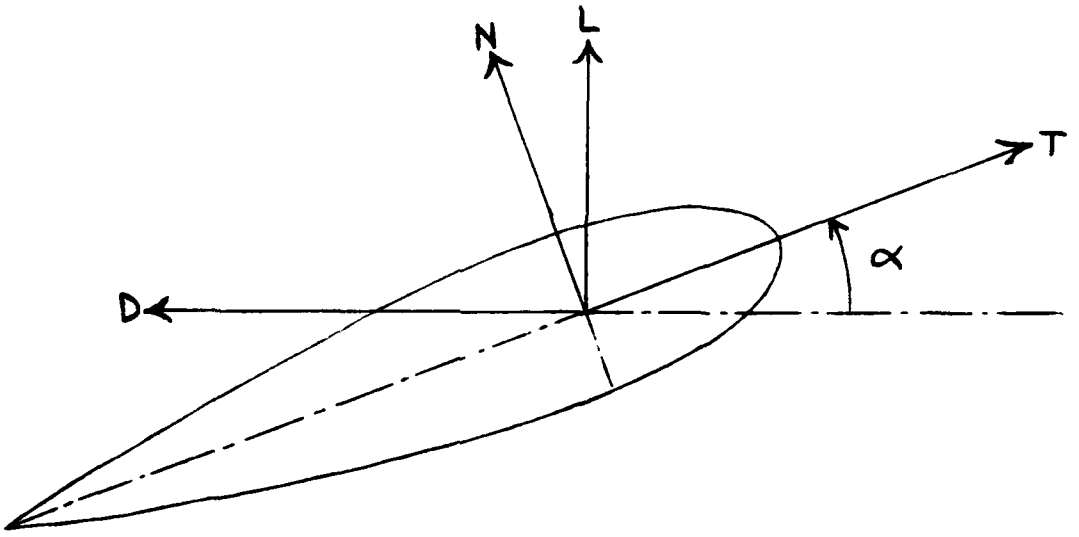

FIG.5 RESOLUTION OF FORCES ON HYDROPLANE

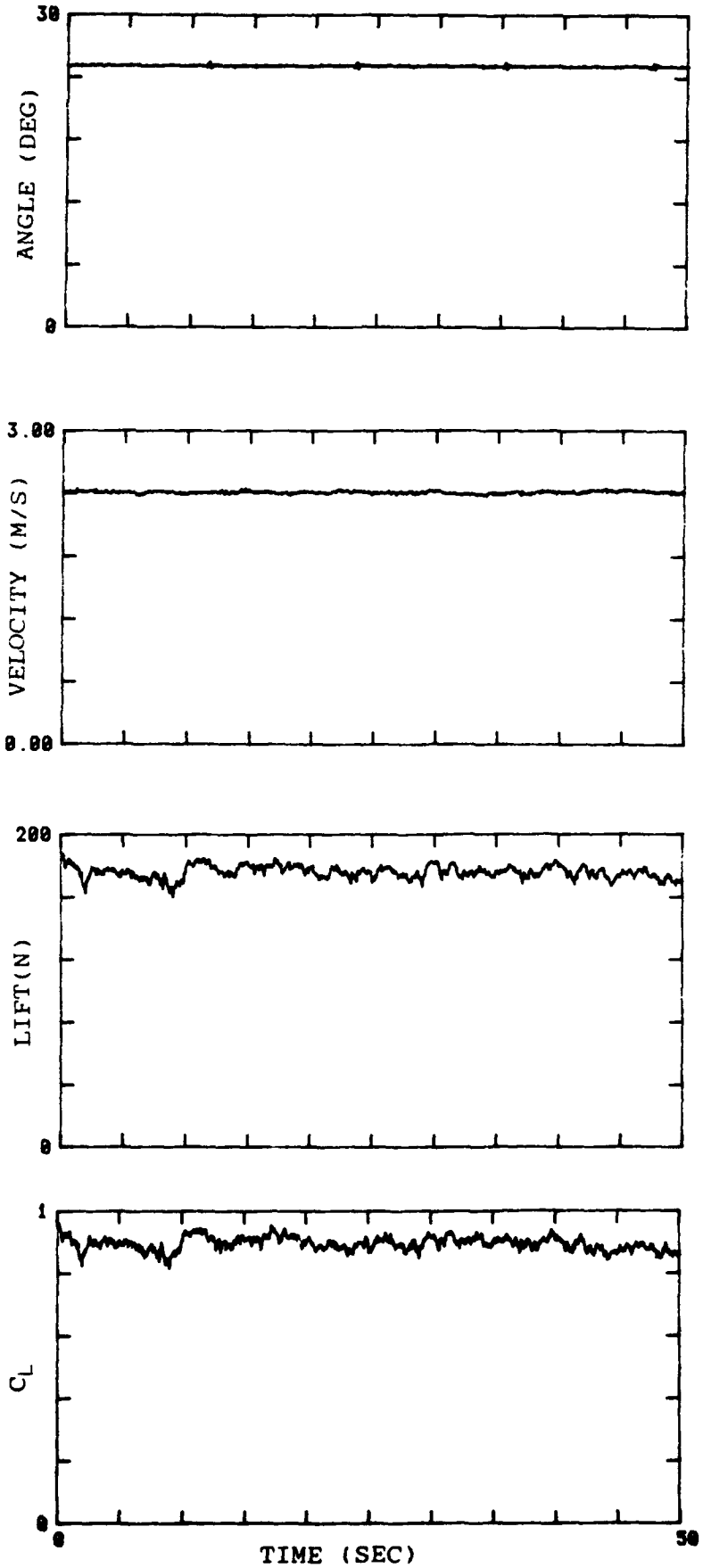

FIG.6 STATIC TIME HISTORY

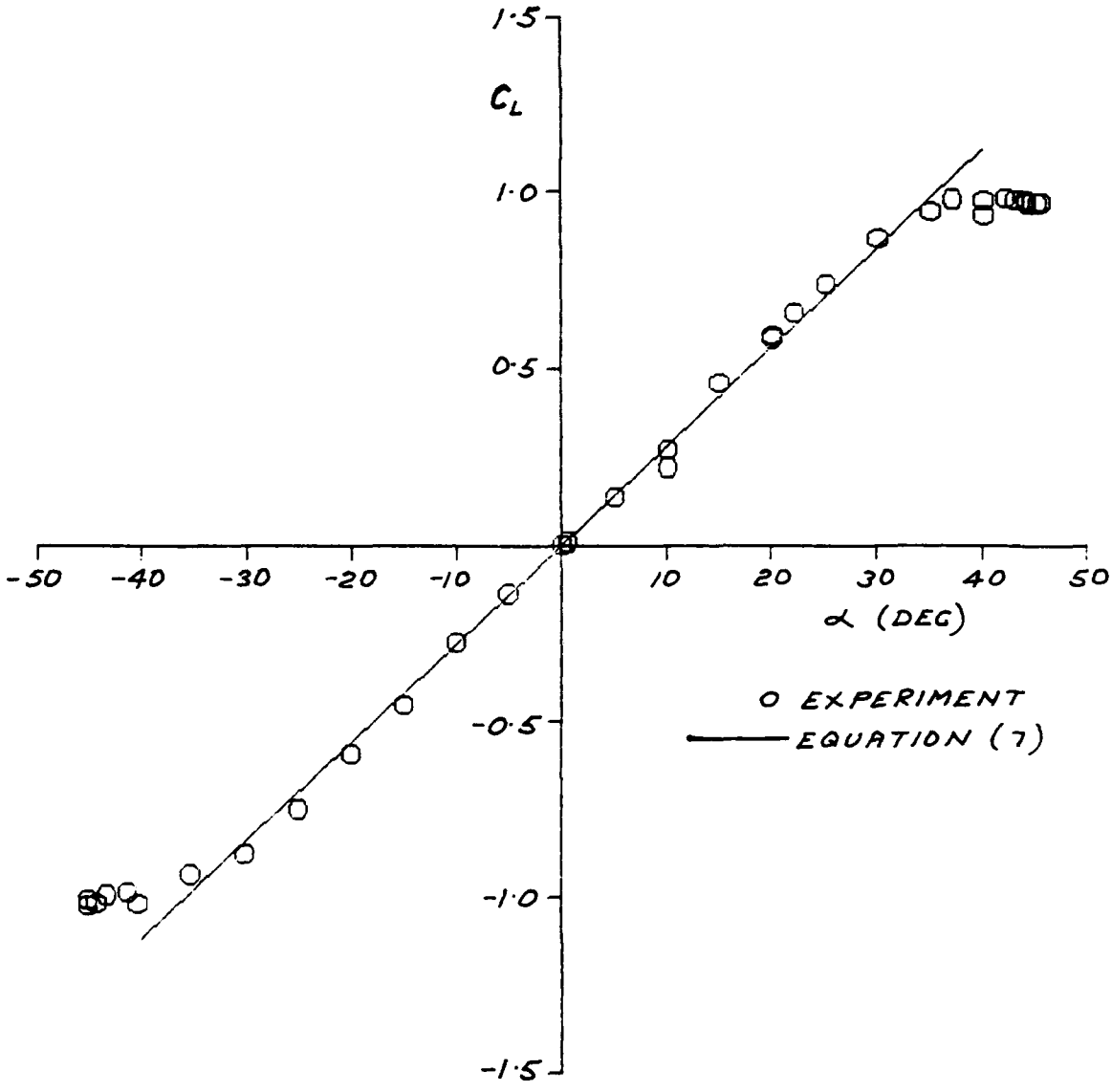

FIG. 7. LIFT COEFFICIENT- ASPECT RATIO 1, STATIC CONDITION

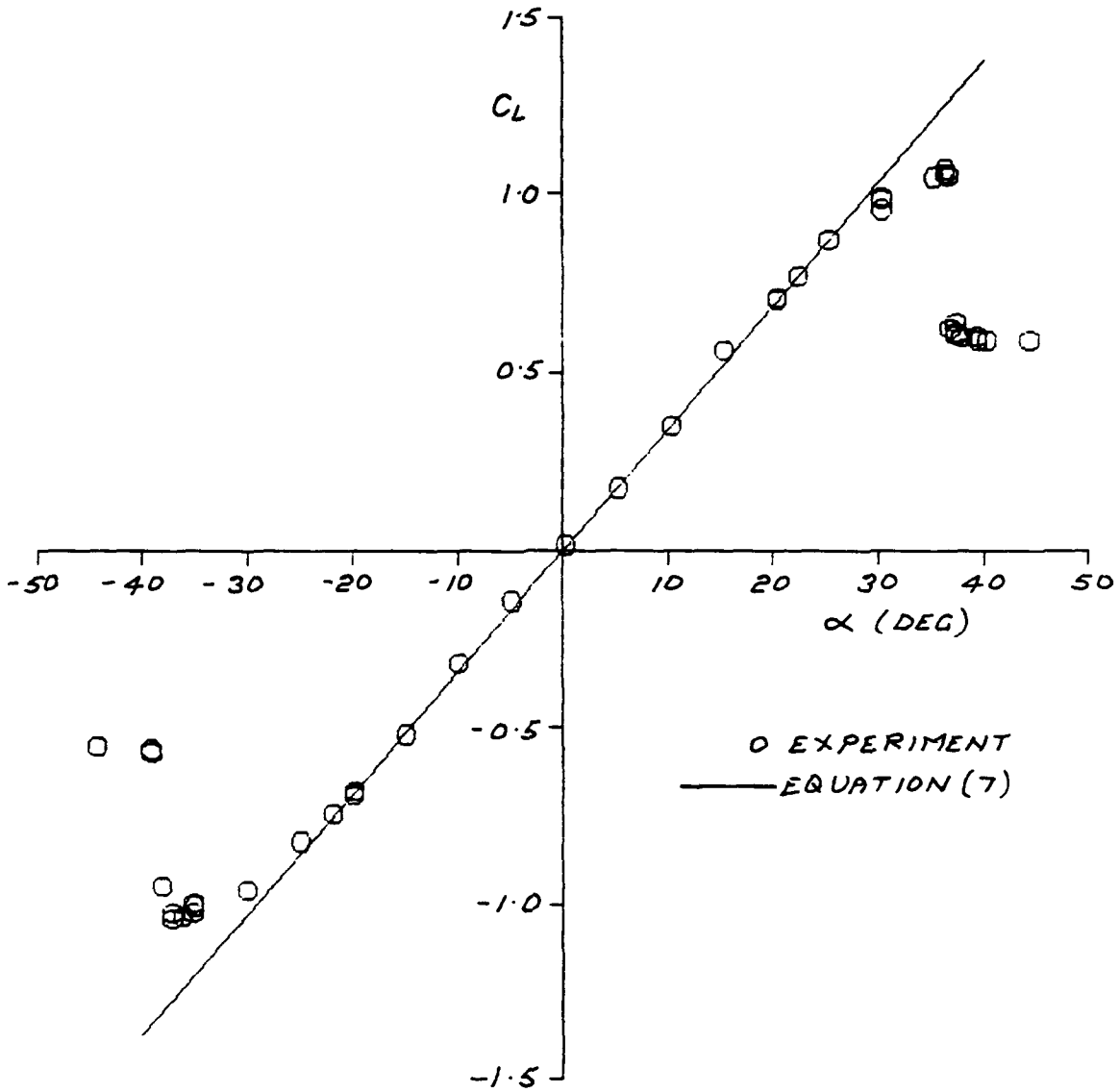

FIG. 8. LIFT COEFFICIENT – ASPECT RATIO 1·5, STATIC CONDITION

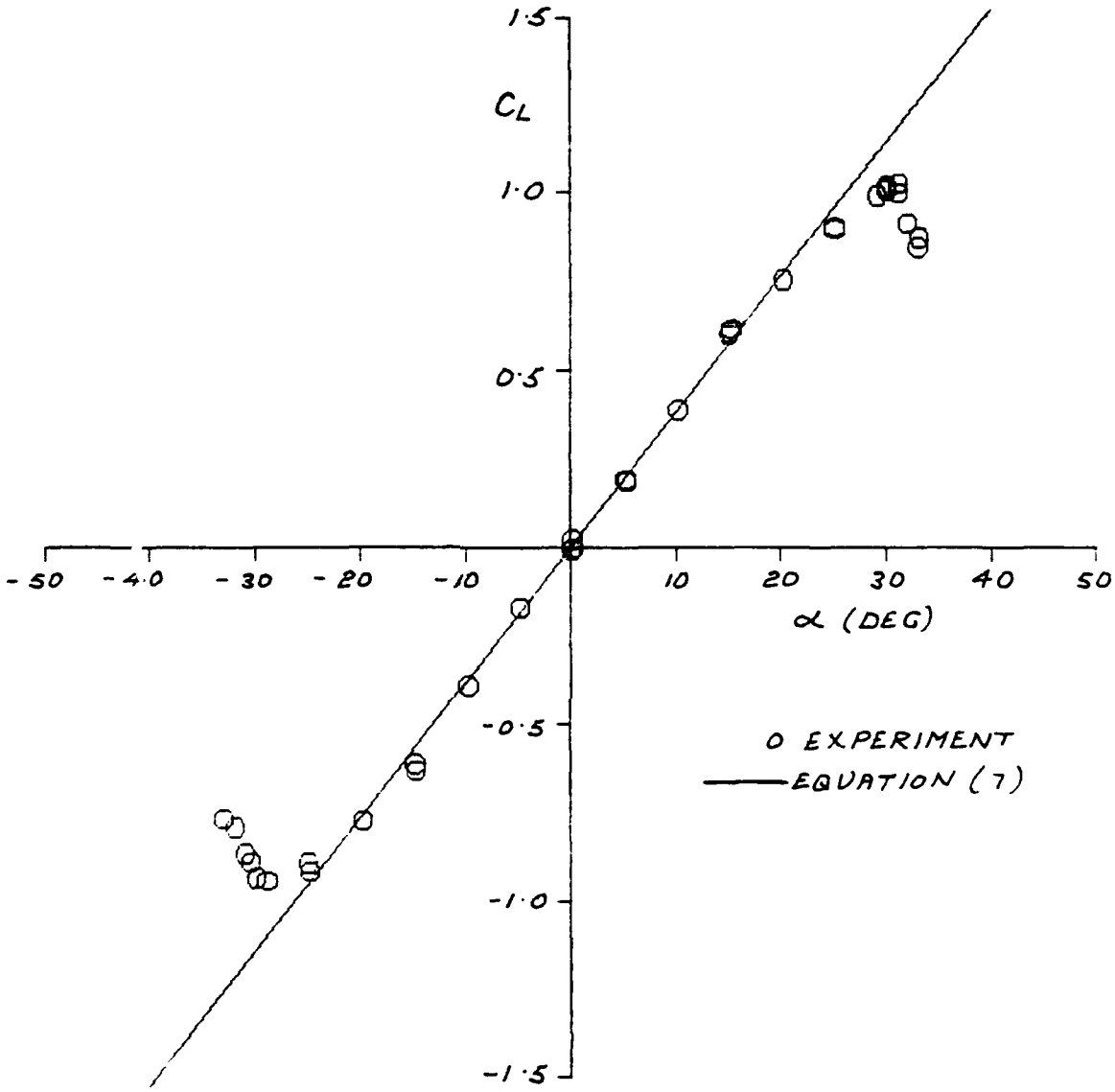

FIG. 9. LIFT COEFFICIENT – ASPECT RATIO 2, STATIC CONDITION

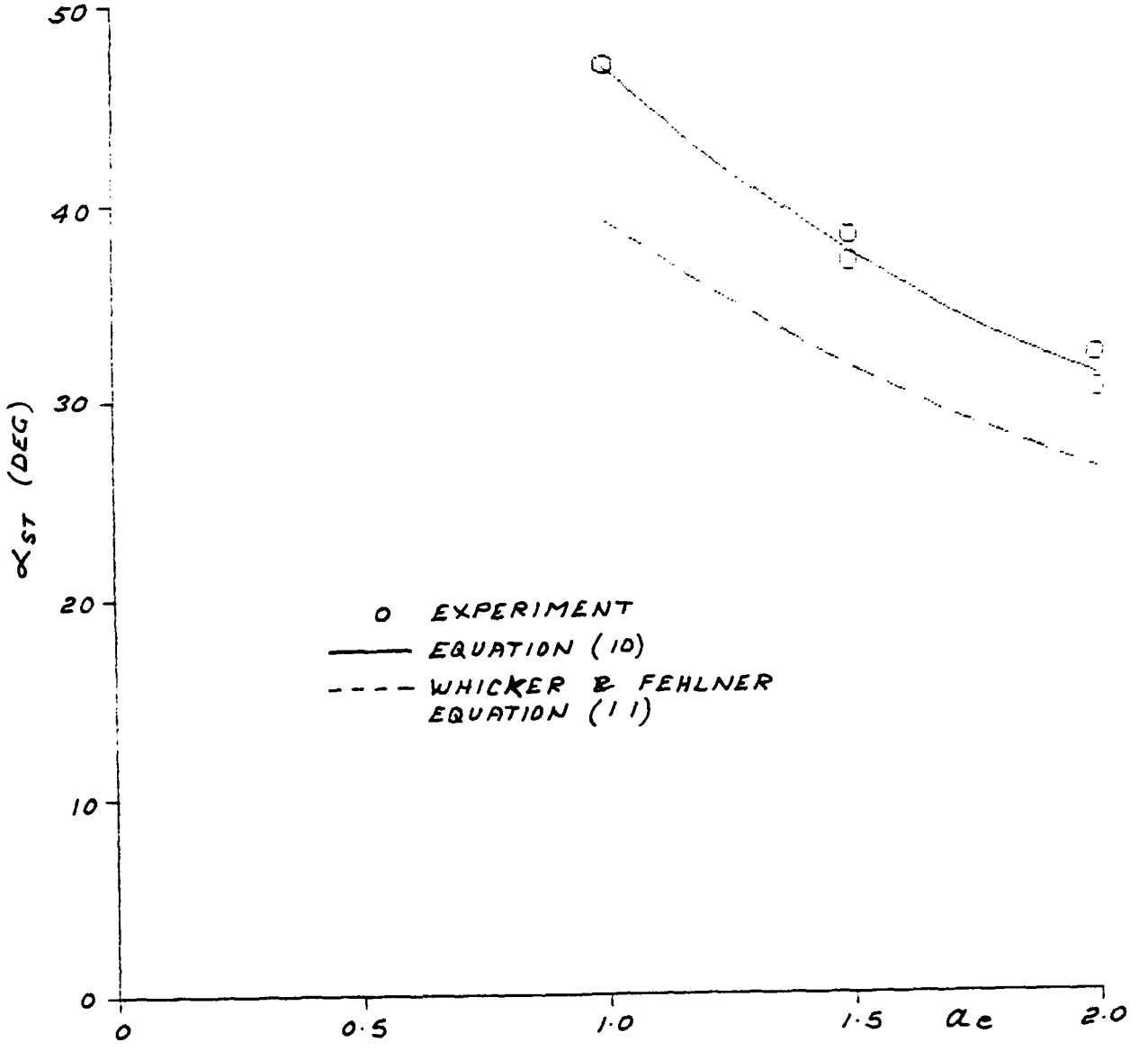

FIG. 10. STALL ANGLE – STATIC CONDITION

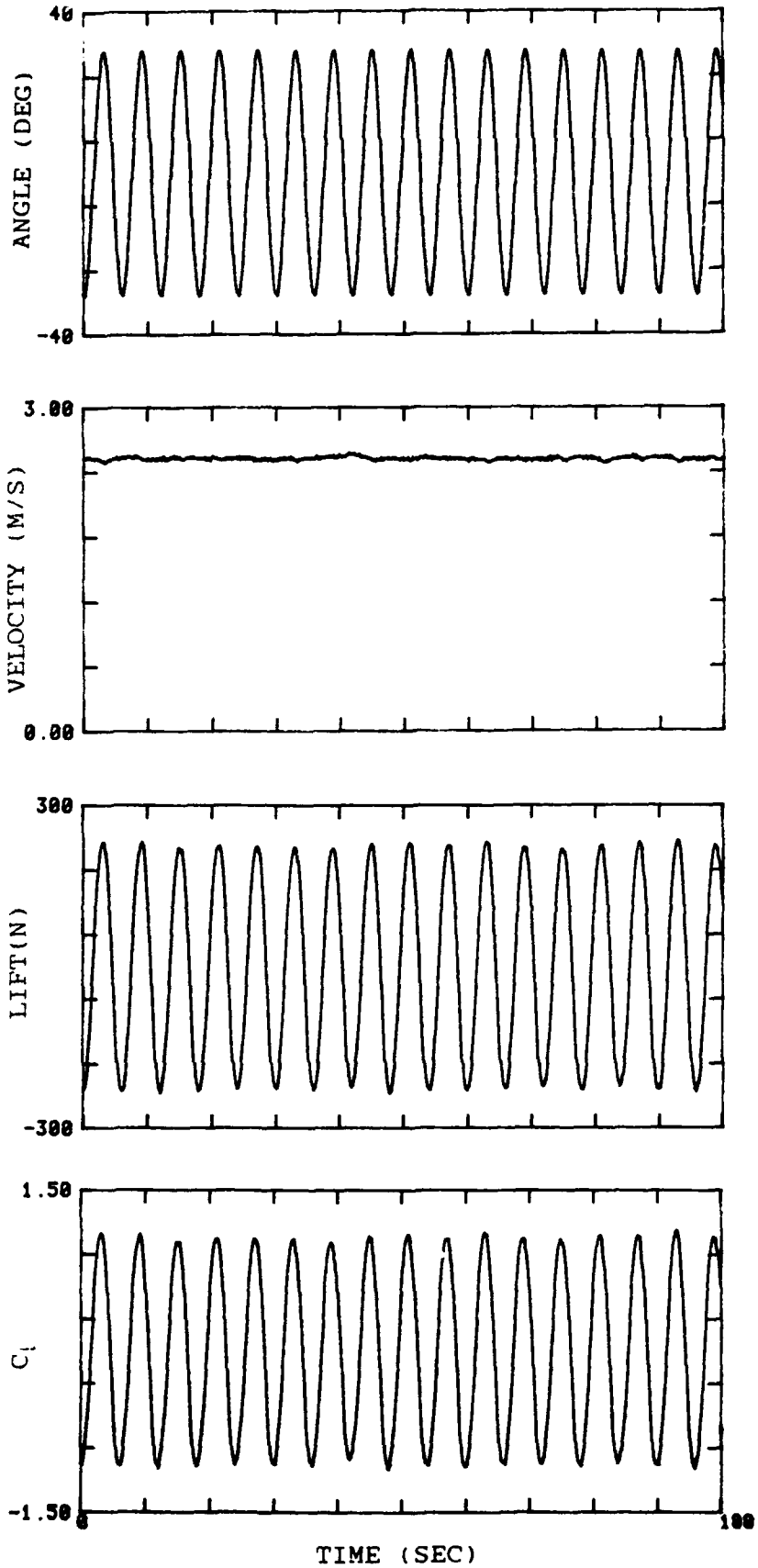

FIG.11 DYNAMIC TIME HISTORY

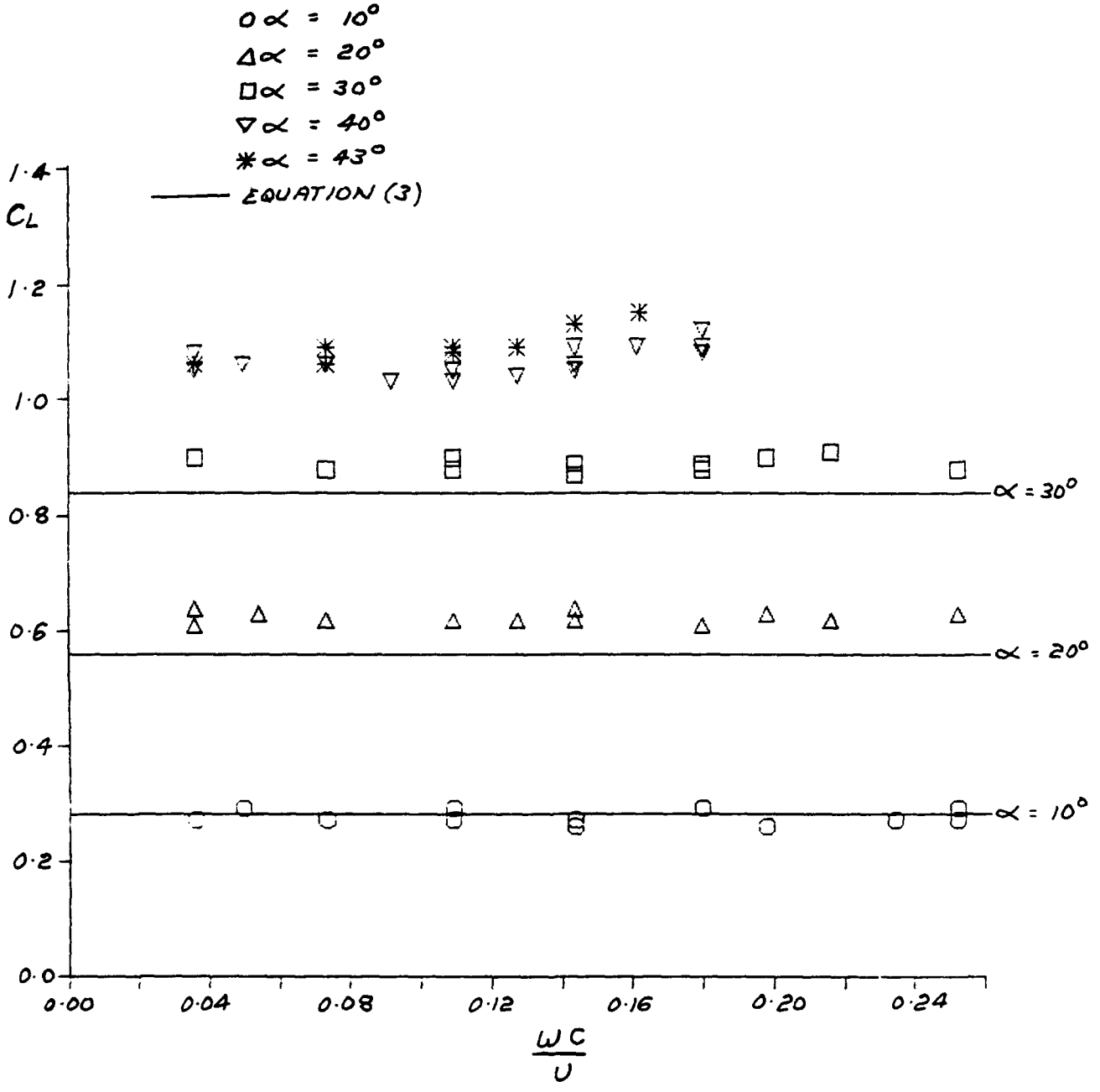

FIG. 12. LIFT COEFFICIENT ASPECT RATIO 1, DYNAMIC CONDITION

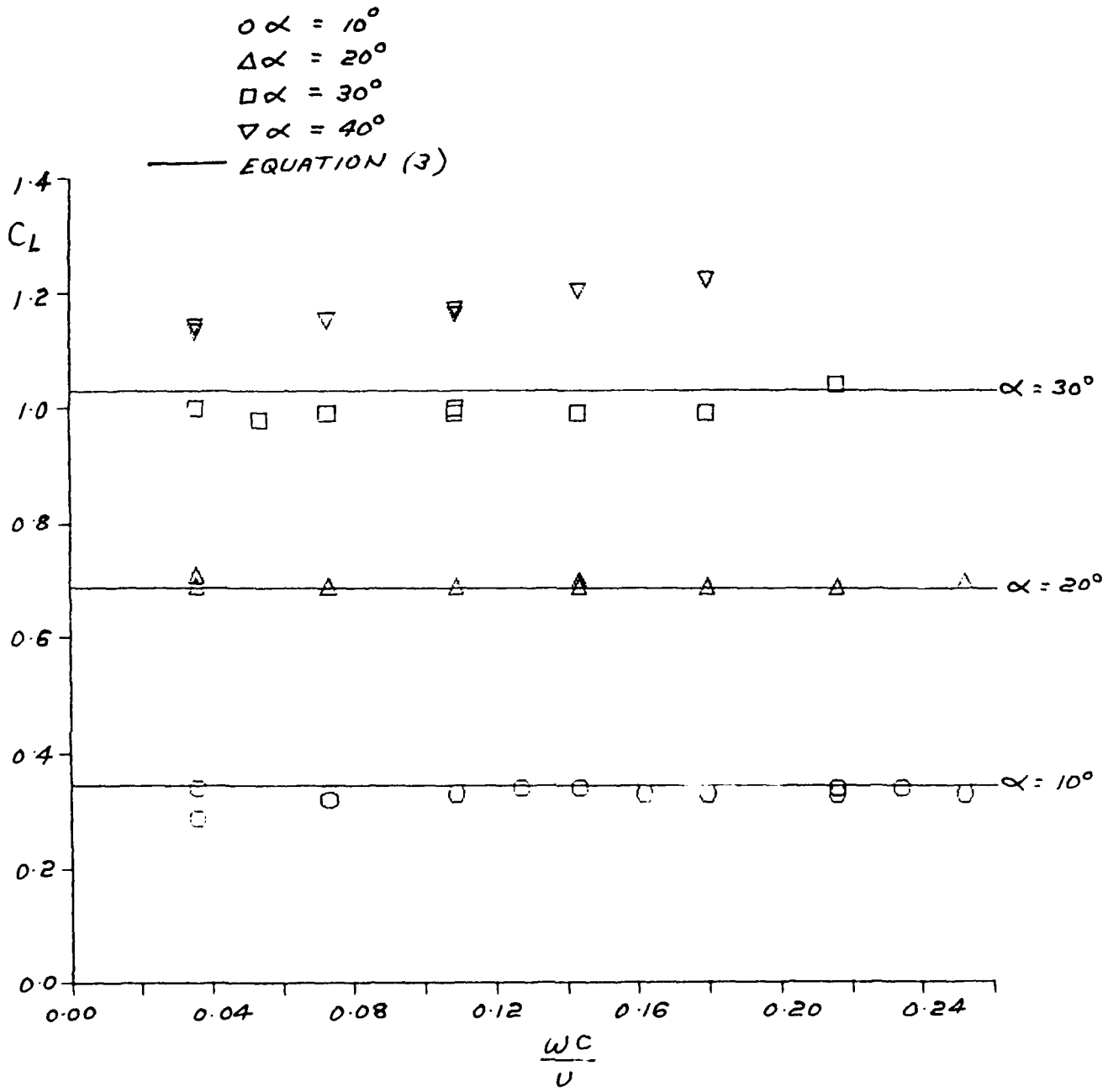

FIG. 13. LIFT COEFFICIENT – ASPECT RATIO 1·5, DYNAMIC CONDITION

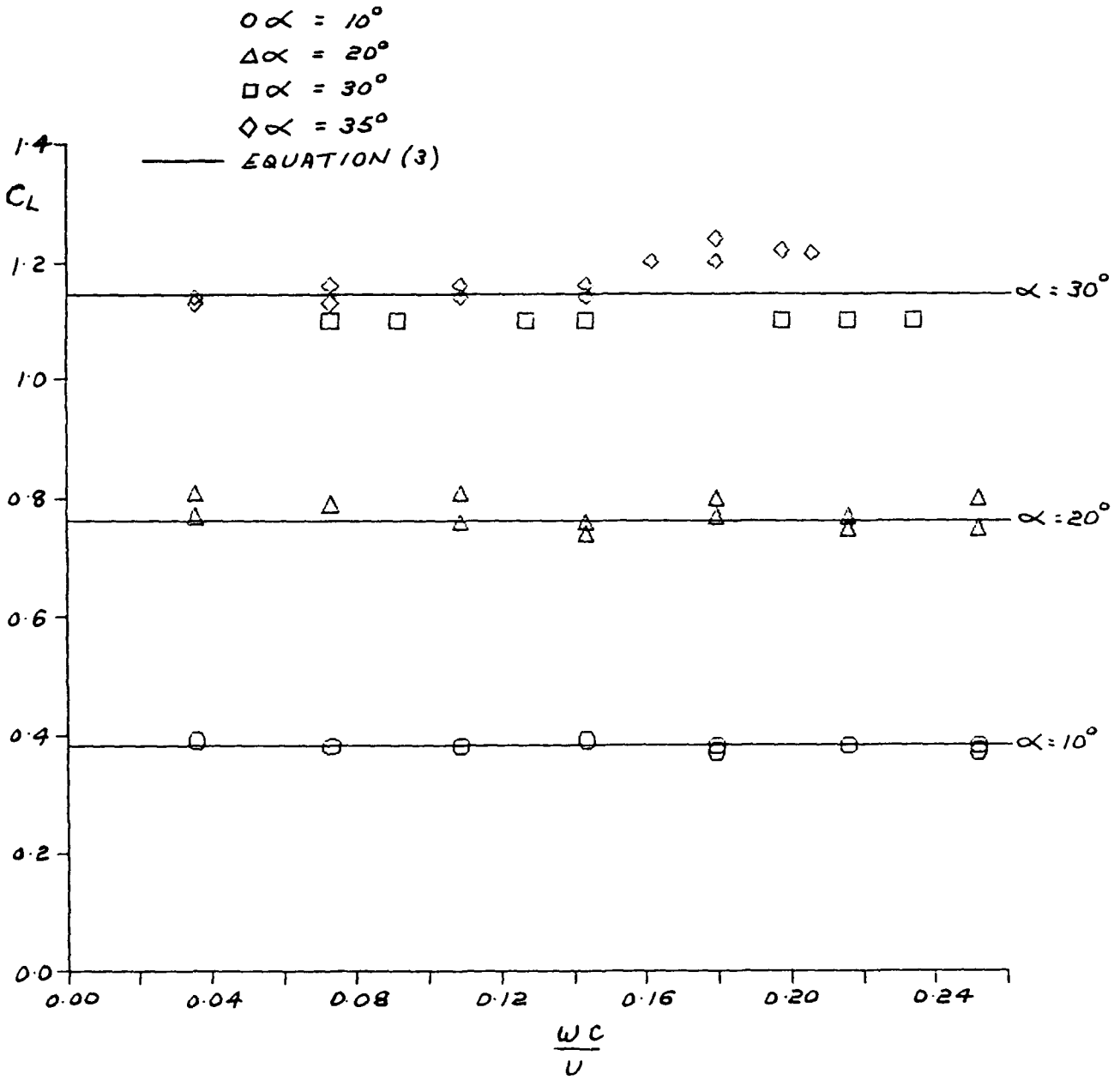

FIG. 14. LIFT COEFFICIENT–ASPECT RATIO 2, DYNAMIC CONDITION

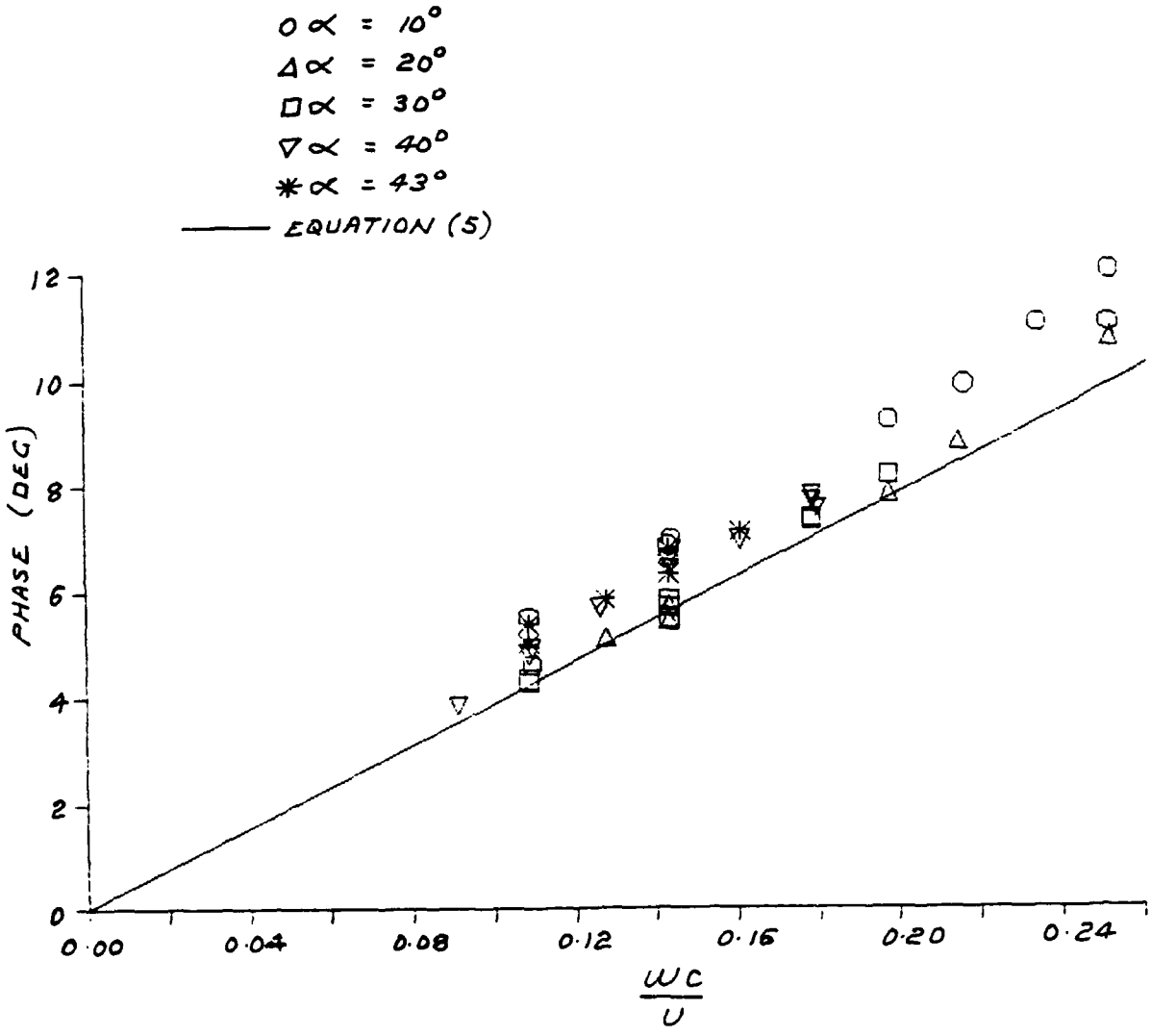

FIG. 15. PHASE ANGLE – ASPECT RATIO 1

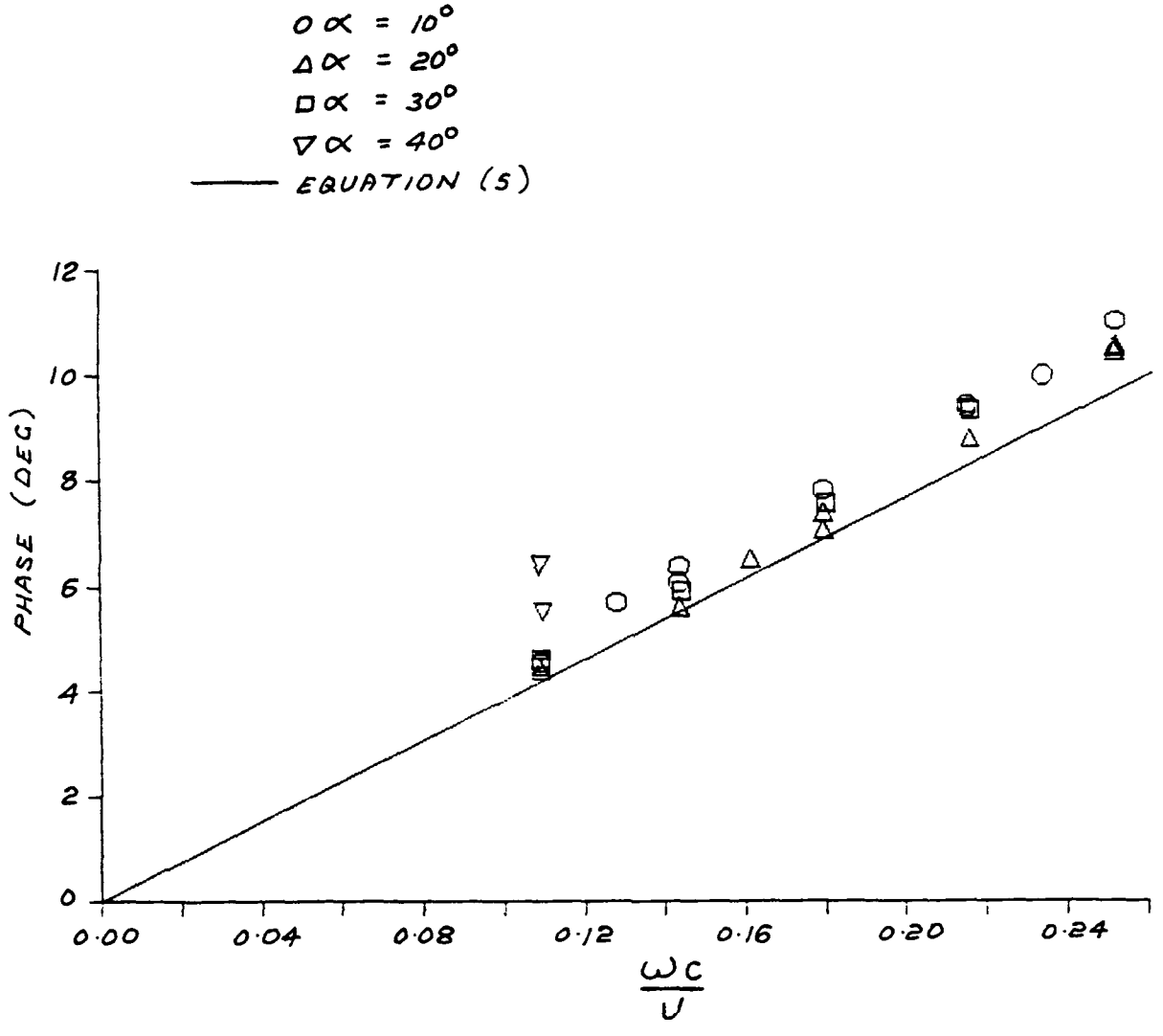

FIG. 16. PHASE ANGLE - ASPECT RATIO 1·5

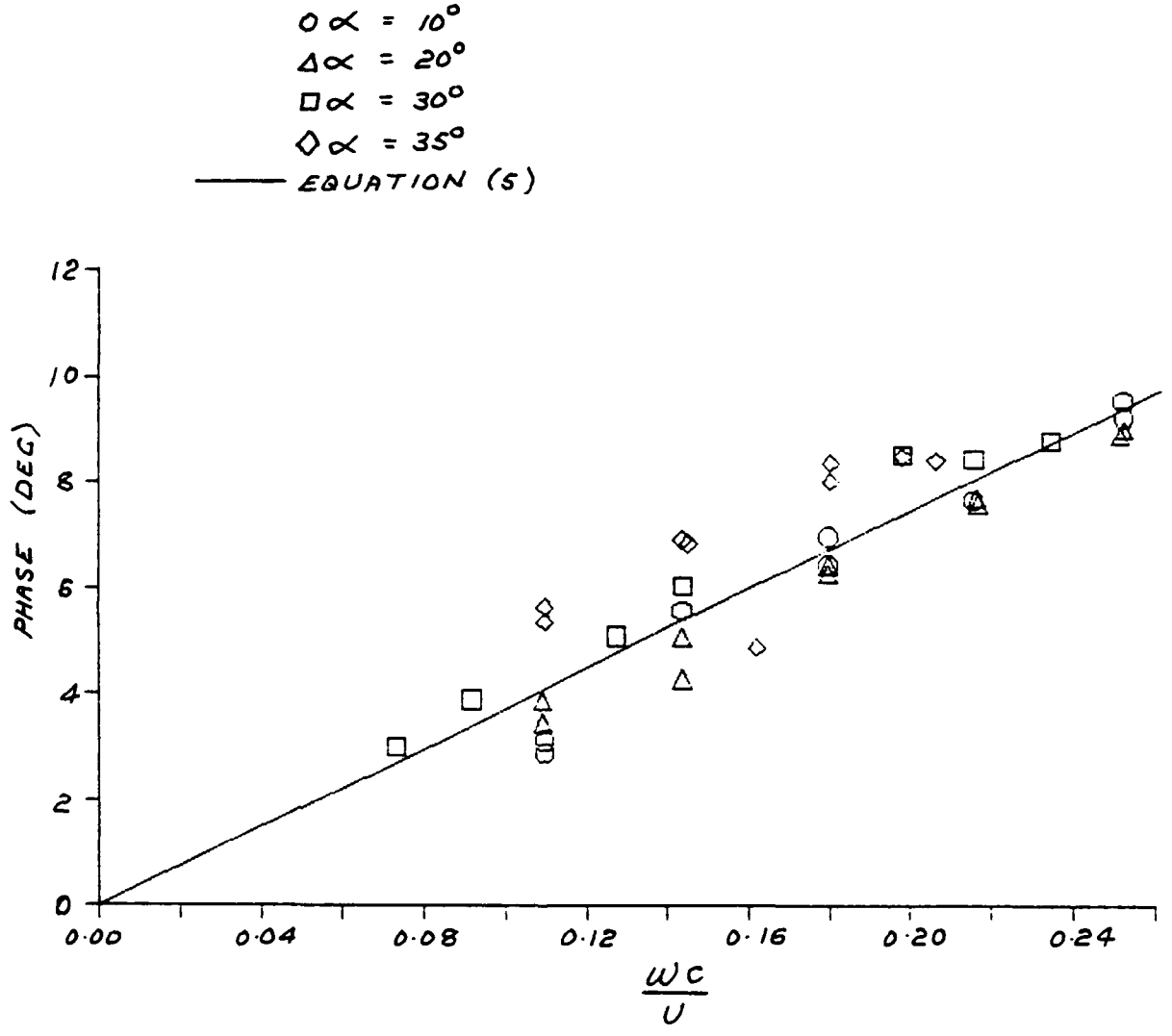

FIG. 17. PHASE ANGLE – ASPECT RATIO 2

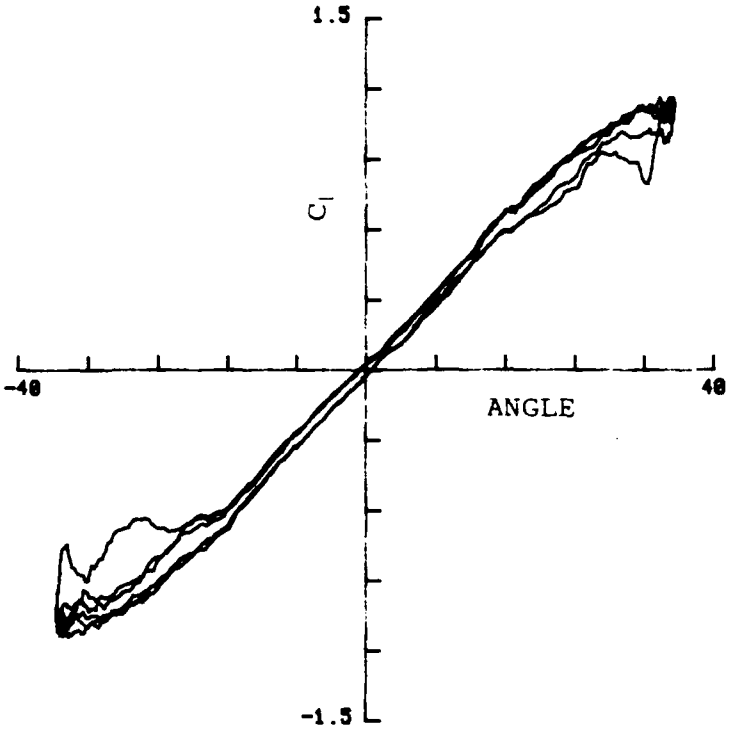

FIG.18(i) DYNAMIC CONDITION - ASPECT RATIO 2
35.5 DEGREES , FREQUENCY 0.055HZ

$\frac{\omega c}{U} = 0.036$

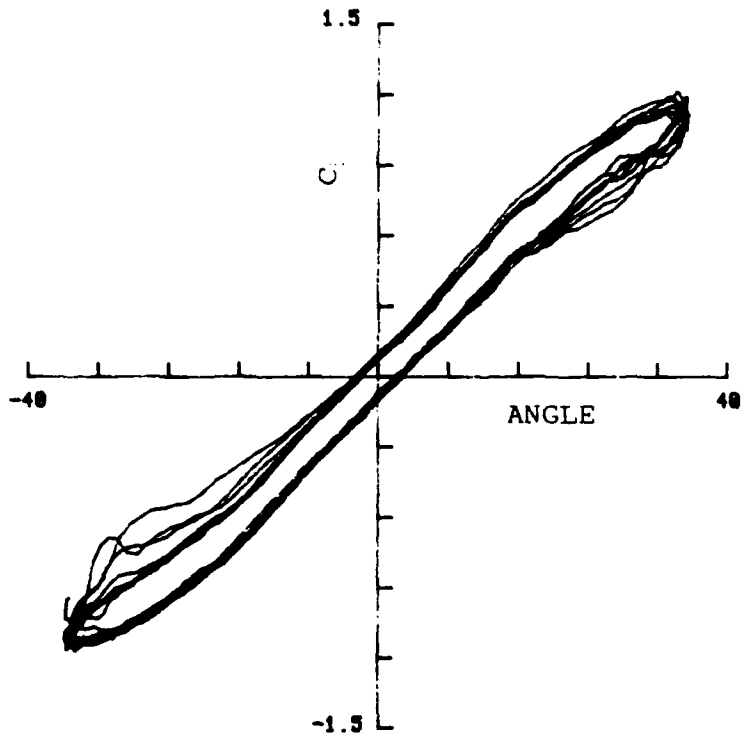

FIG.18(ii) DYNAMIC CONDITION - ASPECT RATIO 2
35.5 DEGREES , FREQUENCY 0.168HZ

$\frac{\omega c}{U} = 0.11$

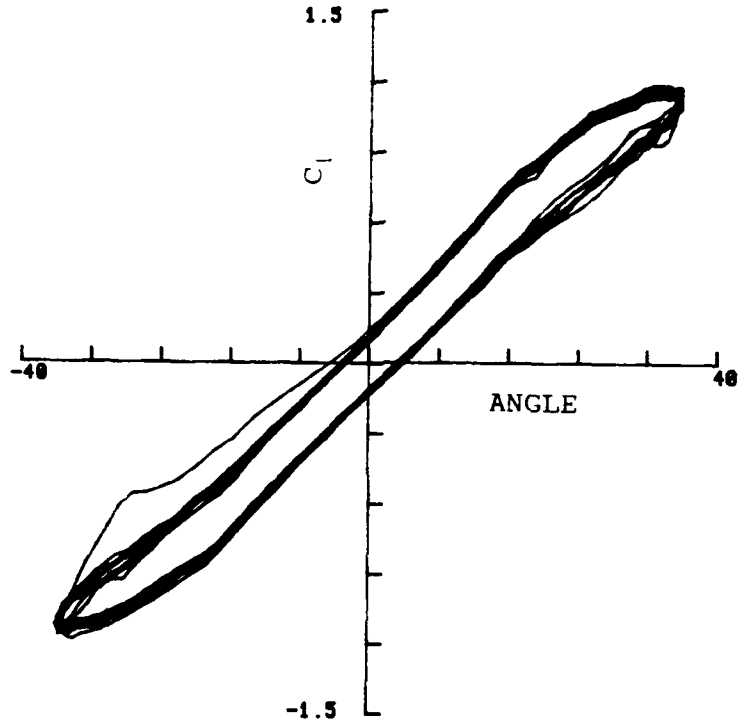

FIG.18(iii) DYNAMIC CONDITION - ASPECT RATIO 2
35.5 DEGREES , FREQUENCY 0.222HZ

$\frac{\omega c}{U} = 0.145$

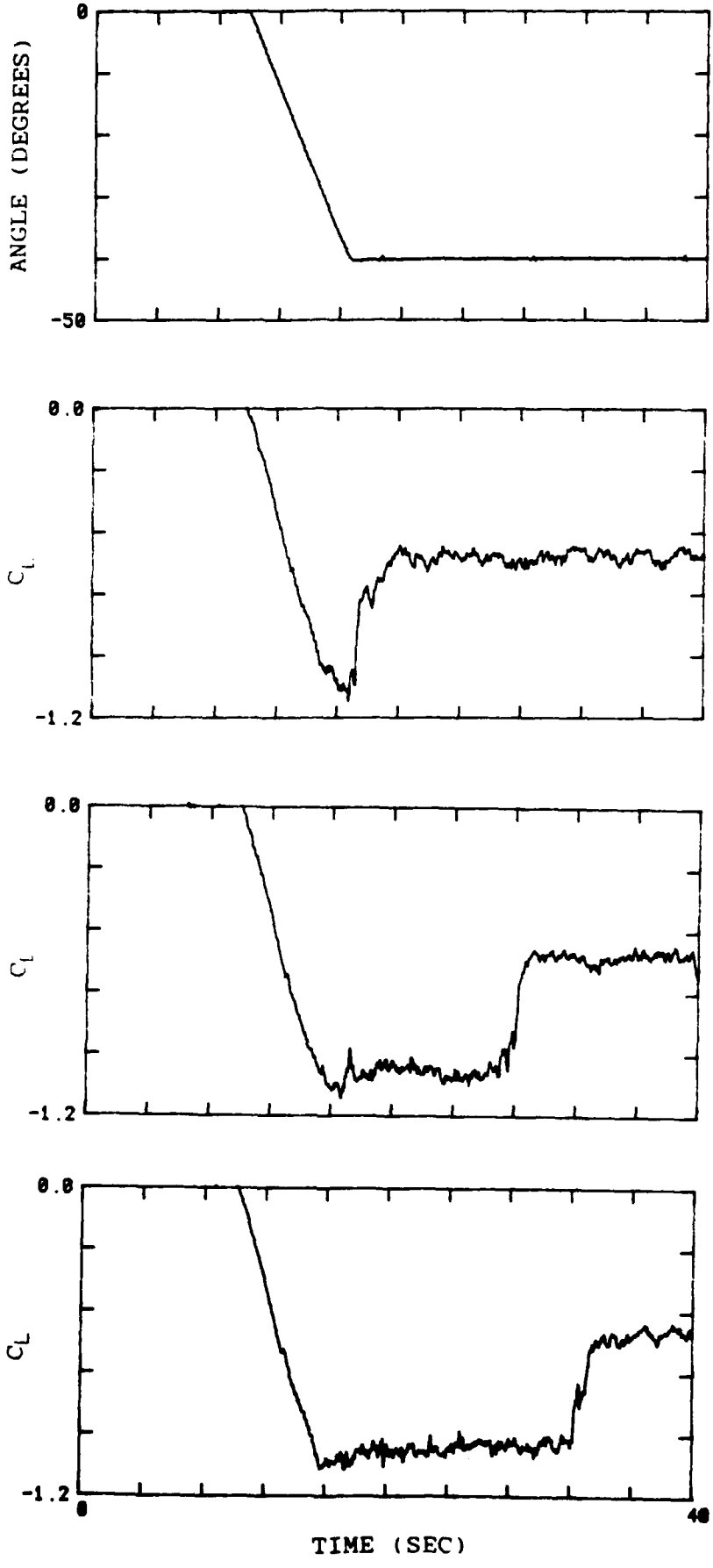

FIG.19 EXAMPLE OF DELAYED STALL - ASPECT RATIO 1.5
41 DEGREES, ANGULAR RATE 6 DEGREES/SEC

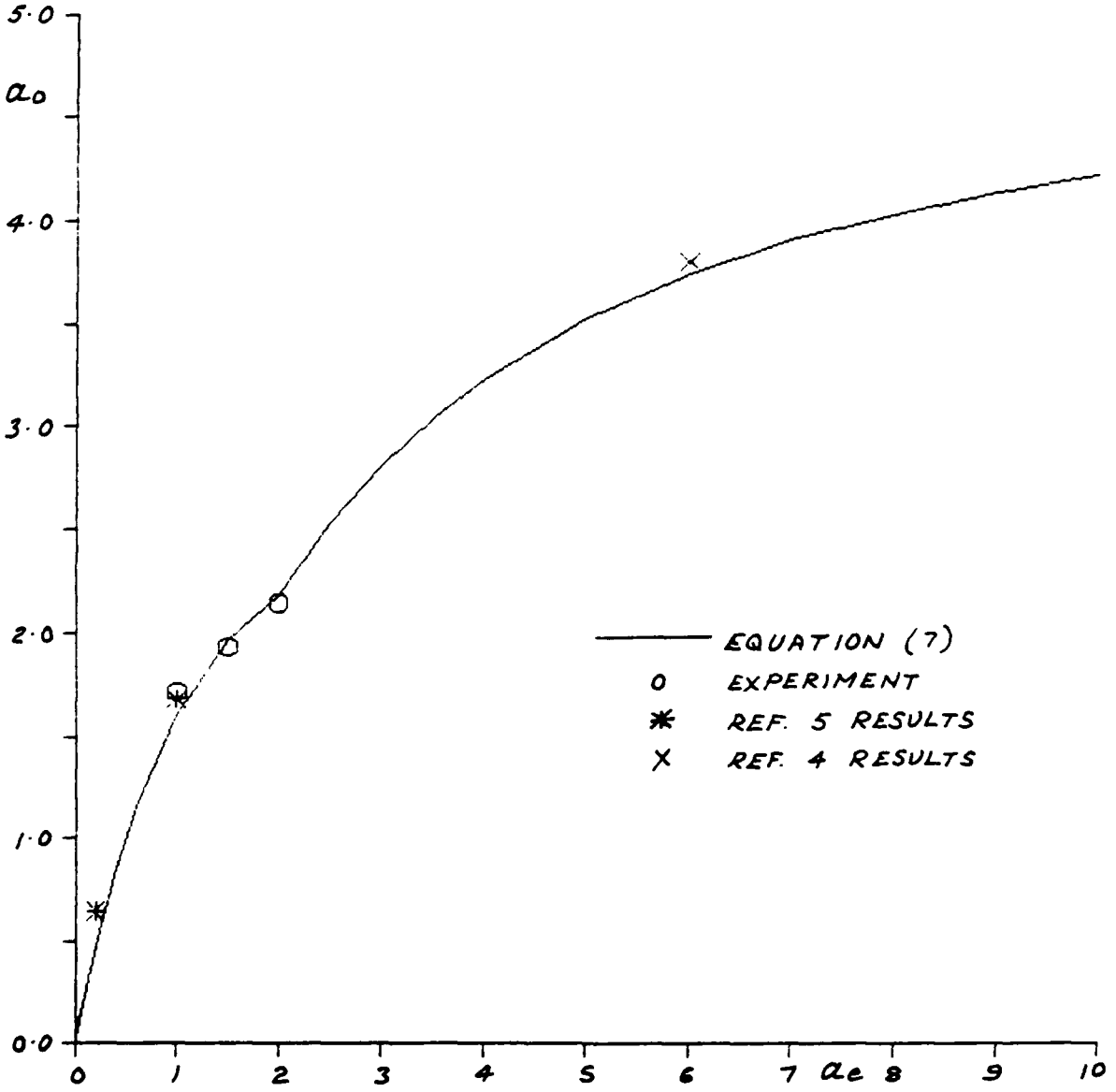

FIG. 20. EMPIRICAL FORMULA FOR COEFFICIENT a_0

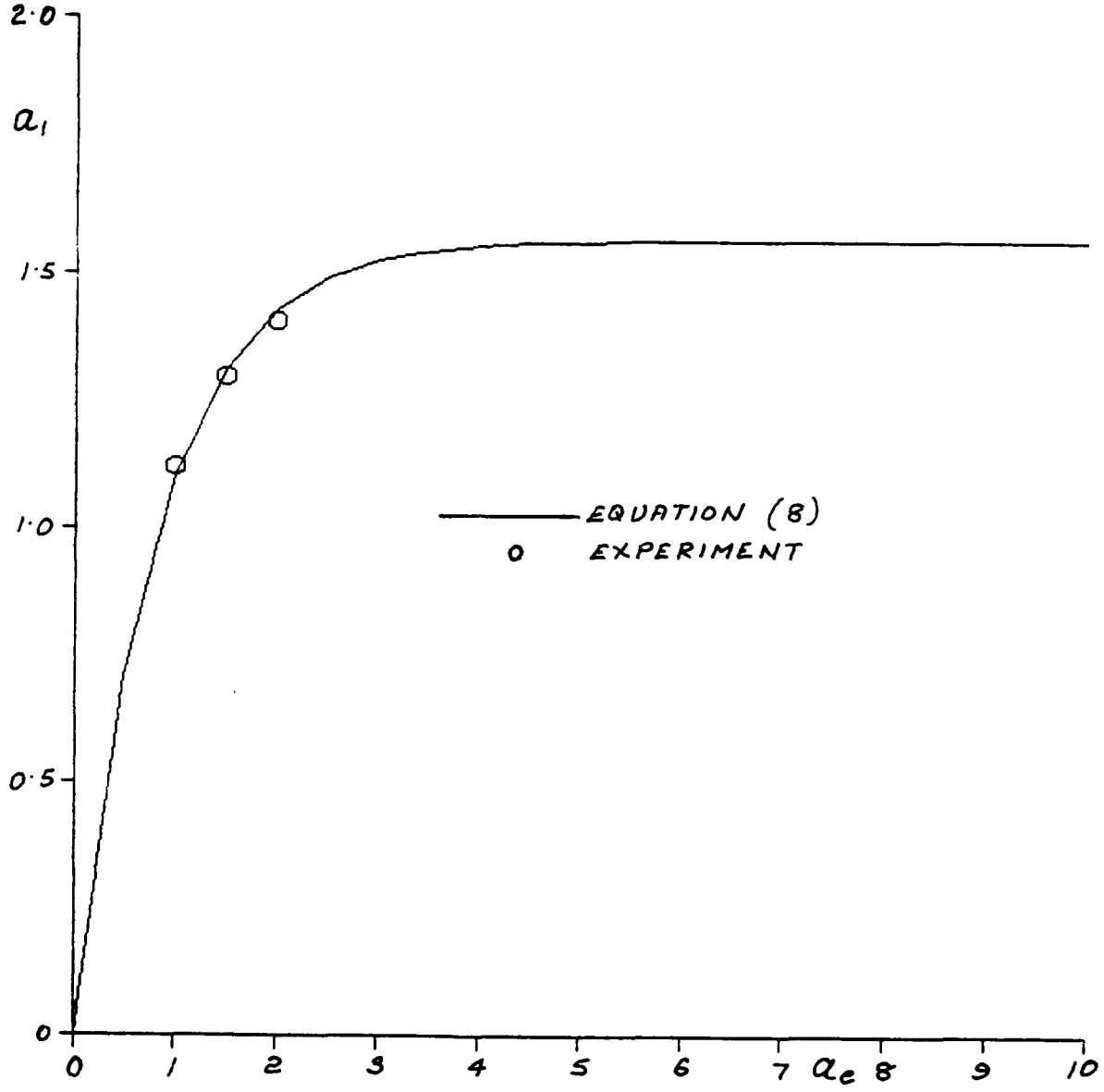

FIG. 21. EMPIRICAL FORMULA FOR COEFFICIENT a_1

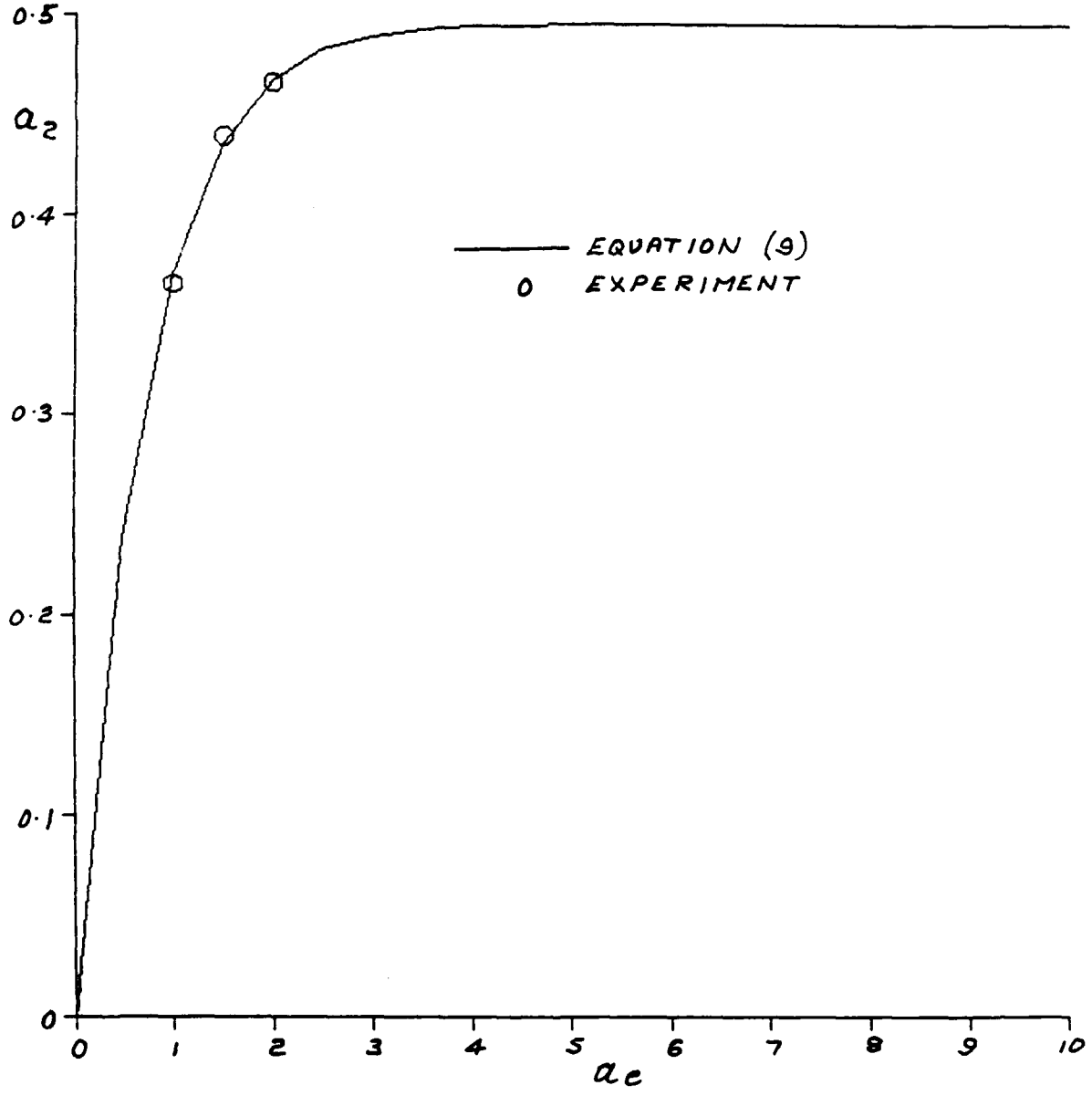

FIG. 22. EMPIRICAL FORMULA FOR COEFFICIENT a_2

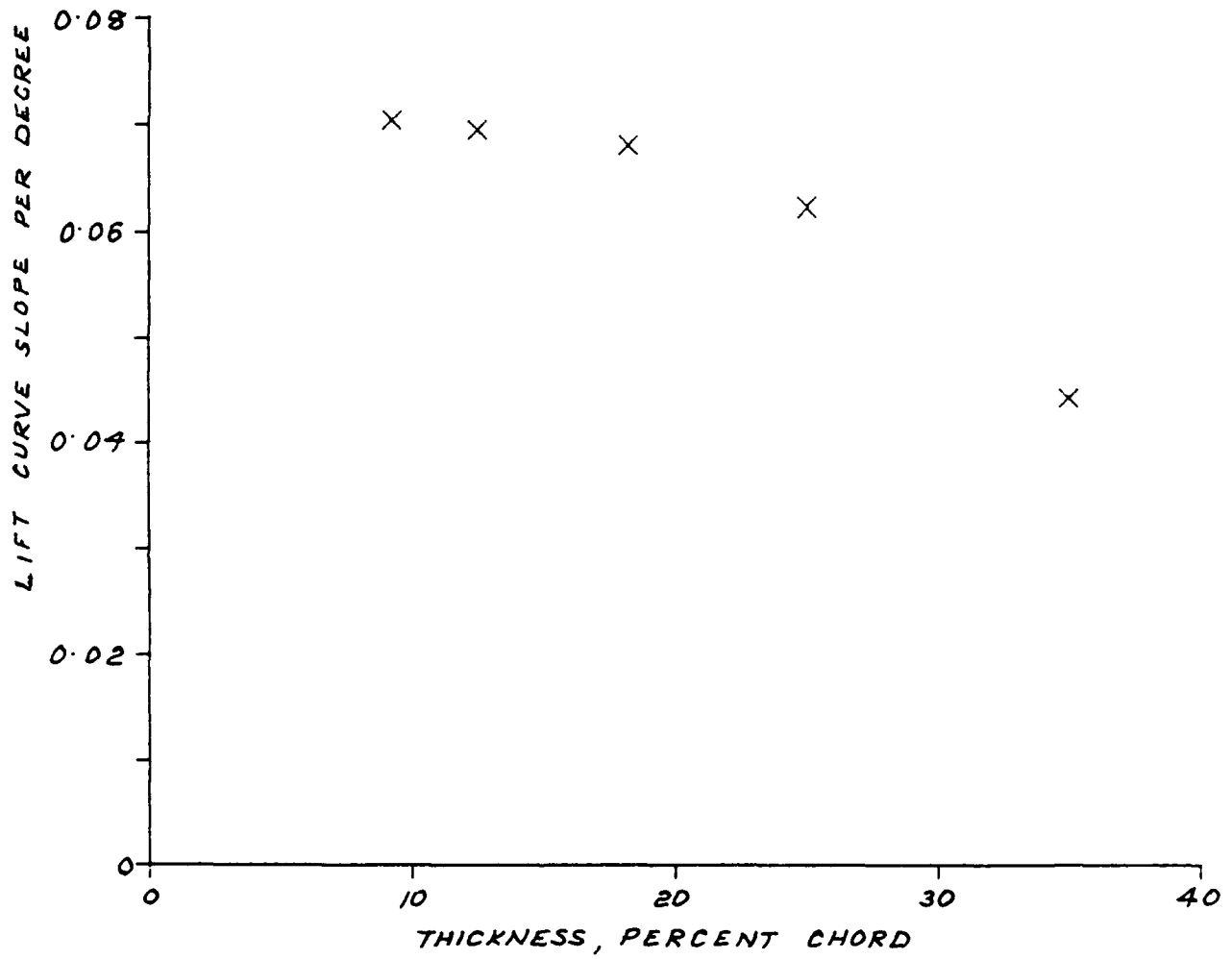

FIG. 23. EFFECT OF THICKNESS ON LIFT CURVE SLOPE NACA OOXX SERIES ASPECT RATIO 6 (REF 4)
$R_e = 4 \times 10^6$

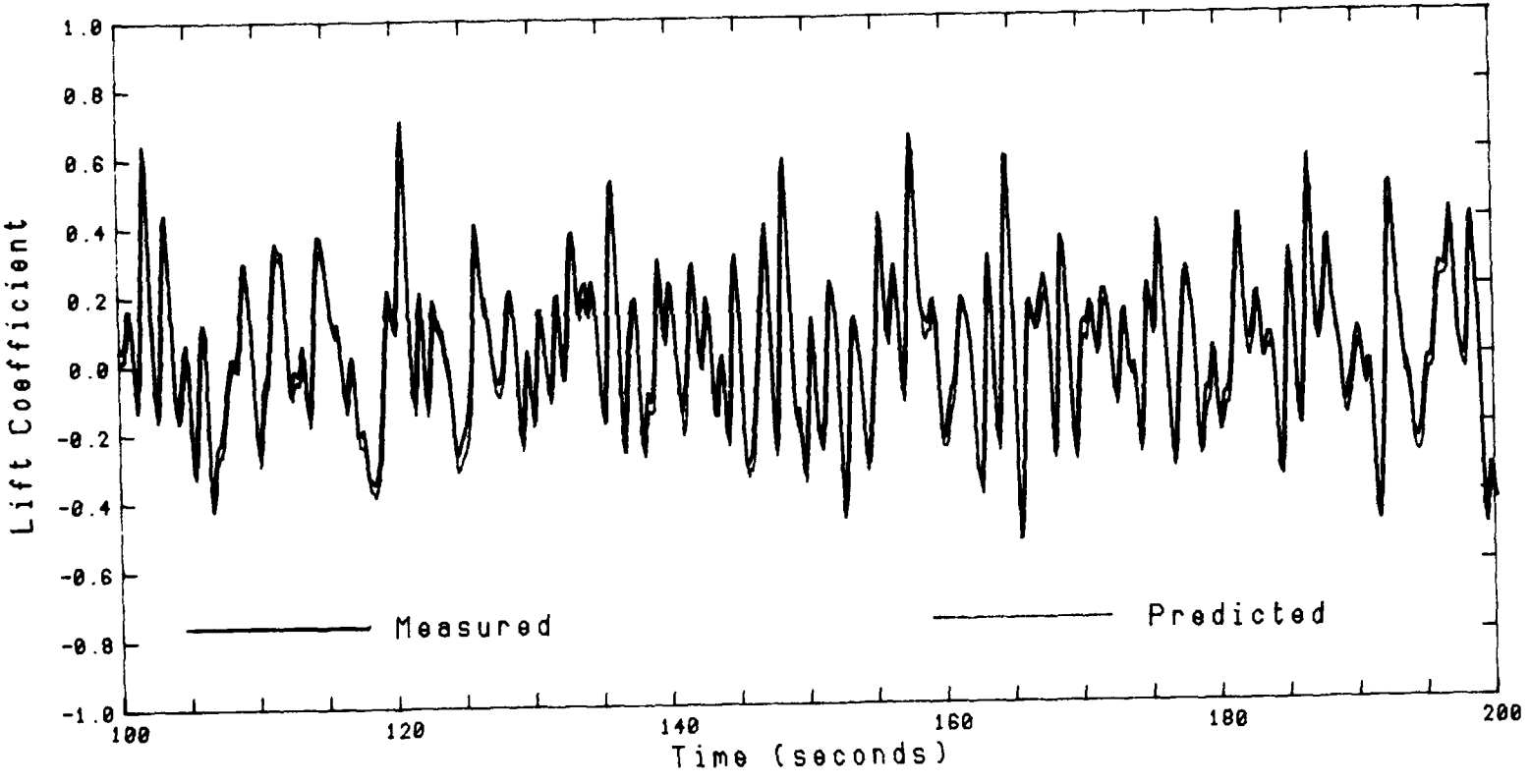

Fig 24 COMPARISON OF C_L FROM EQUATION (3) WITH RANDOM SIGNAL RESULTS

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Abstract
This Technical Memorandum describes experiments in the Circulating Water Channel to measure lift forces on low aspect ratio hydroplanes under static and dynamic conditions. Empirical equations to represent the results are given.

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